TECHNICAL DOCUMENT 3298
September 2015

Micro-Electro-Mechanical Systems (MEMS) Fabrication Course Projects Review for FY15

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Approved for public release.

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ADMINISTRATIVE INFORMATION

This work was prepared by the Advanced Circuit Technology Branch (Code 55250) of the Networks Division (Code 55190), Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA. SSC Pacific's Naval Innovative Science and Engineering (NISE) Program provided funding for this Workforce Development project.

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SB

SSC Pacific S&T *Workforce Development*
MEMS Fabrication Course
Projects Review for FY15

Presented to:

San Diego State University (SDSU) Students and Staff

June 18, 2015

Paul D. Swanson et. al.

7.1

Code 55250

▼ *PI: Dr. Paul D. Swanson, Engineer*

Paul Swanson received a Ph.D. in electrical engineering from the University of Illinois at Urbana Champaign. As a post-doc he fabricated devices at the Cornell NanoScale Science & Technology Facility (CNF). He was an industrial user at Stanford Nanofabrication Facility (SNF) and in charge of Nanogen's internal semiconductor fabrication clean-room. He has 33 issued patents, 17 refereed publications, and is a listed author on six conference proceedings. At SSC Pacific, he invented Time Domain Switched Inertial Sensors (TDSIS). (Not a SMART scholarship recipient.)

▼ *Co-PI: Bruce W. Offord, Engineer*

Bruce Offord received his B.S. in Engineering Physics from the University of California, San Diego. Bruce has more than 13 patents, has authored more than 20 publications, received a Navy Meritorious Civilian Service award, an Exemplary Achievement award, Distinguished Publication and Excellence in Publications awards, and Navy Award of Merit for Group Achievement. Mr. Offord has more than 25 years of experience in integrated circuit design, fabrication, and testing. He has worked on R&D projects for the Navy, DARPA, ARDA, and commercial entities in radiation hardened silicon fabrication processes, radio frequency switches, displays, sensors, and carbon-nanotube switches. (Not a SMART scholarship recipient.)

Class of FY15

SSC PACIFIC MEMS Course Student/Project List

Student	Code	Project
Wayne McGinnnis:	71730	Precise Front to Back Side Alignment Using Through Wafer Etching
Jonathon Oiler:	81320	Micro-Fluidic Flow Channel for Miniaturized Flow Cytometer
Howard Dyckman:	71730	Infrared Waveguides
Teresa Emery:	55360	Bistable MEMS systems for Energy Harvesting
Sam Chieh:	55250	mm-Wave Antennas on Quartz Substrate
Everly Yeo:	55250	mm-Wave Antenna Arrays
Ben McCoy:	55230	MEMS for Antenna

Instructors:

- Paul D. Swanson
- Bruce W. Offord
- Prof. Samuel K. Kassegne (SDSU)

▼ Wayne McGinnis:

Backside Alignment without a Backside Mask Aligner

Presenter:

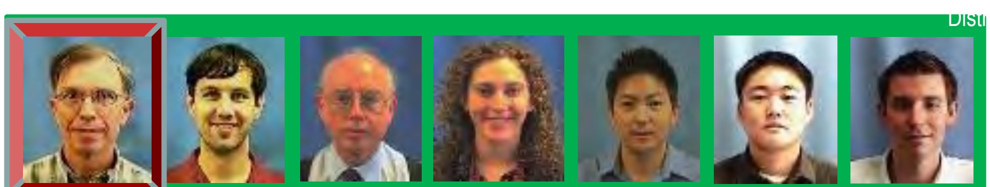
Wayne McGinnis

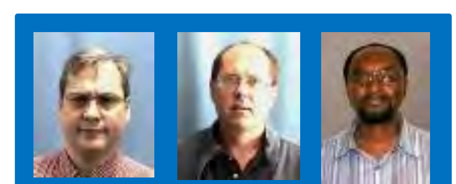
SSC Pacific, Code 81320

Presented to:

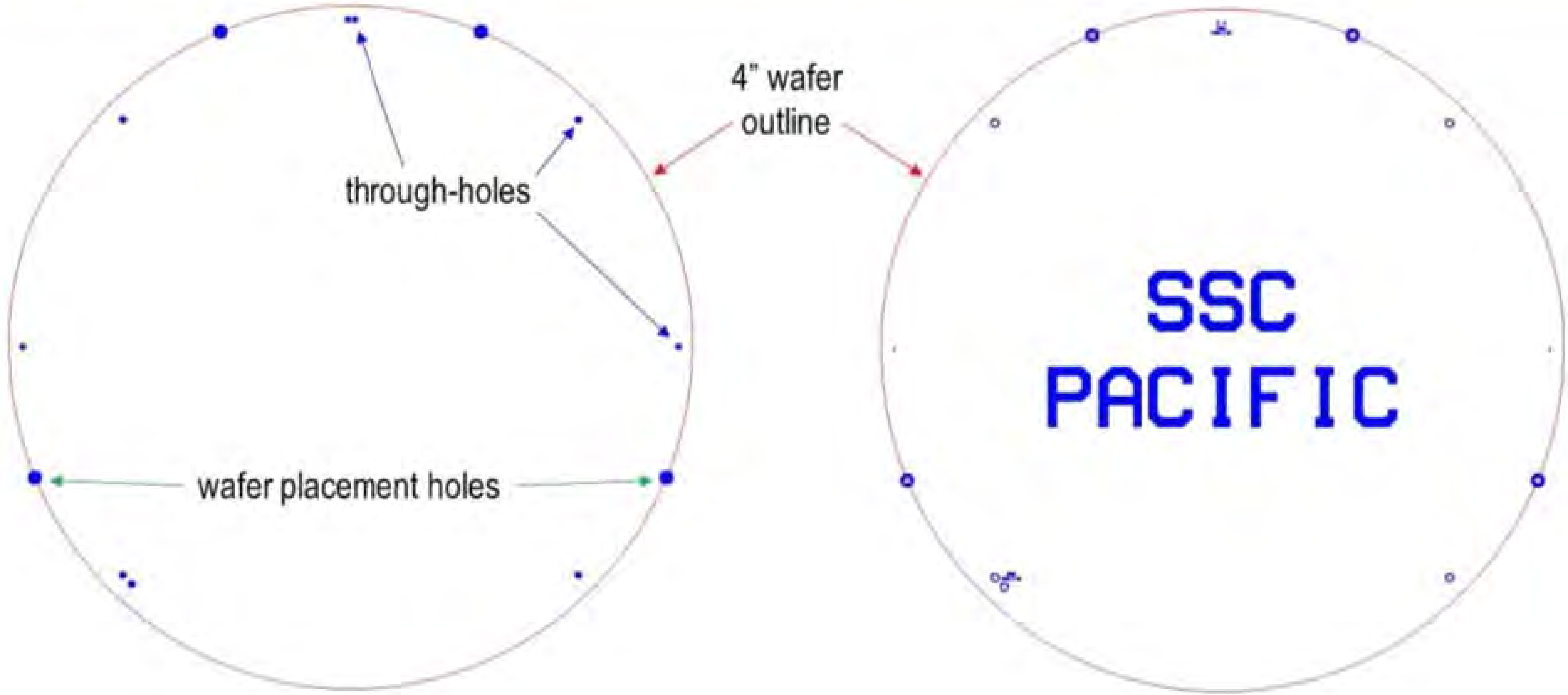
SDSU MEMS Course Participants

June 2015





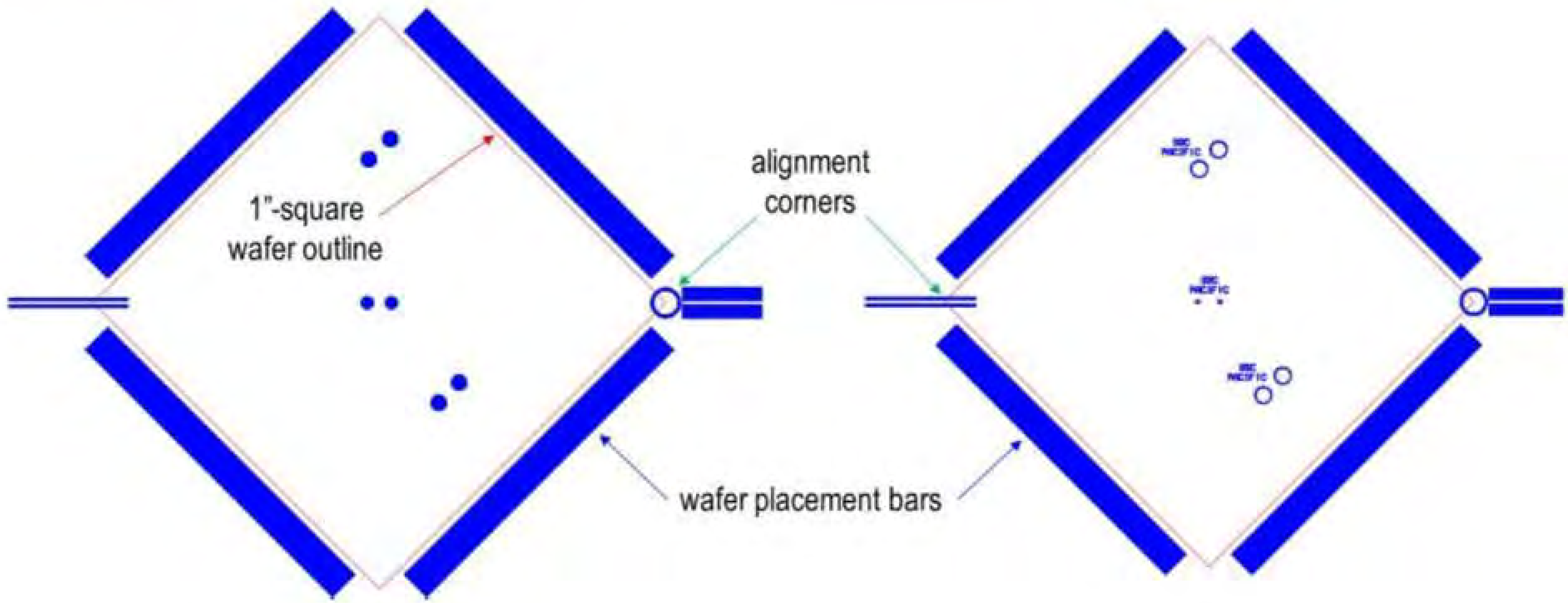
Method 1: Use etched through-holes as alignment marks



Bottom pattern
(looking "through" wafer from the top)

Top pattern

Method 2: Use wafer piece corners as alignment marks

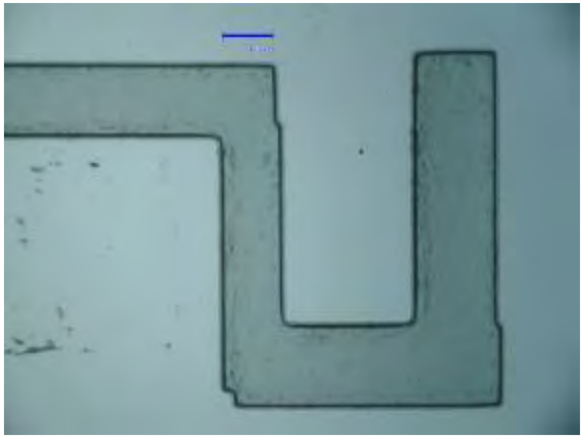


Bottom pattern
(looking "through" wafer from the top)

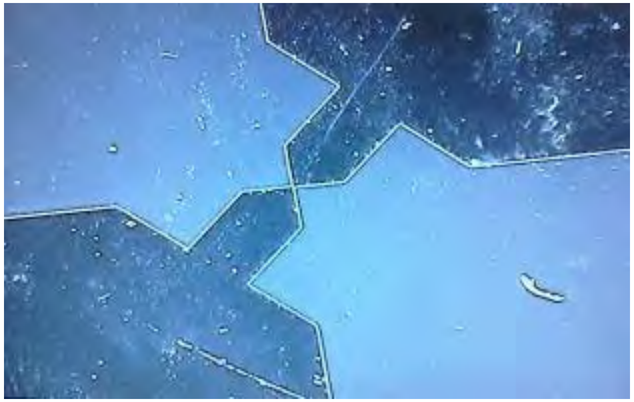
Top pattern

Process Steps and Results for Method 1

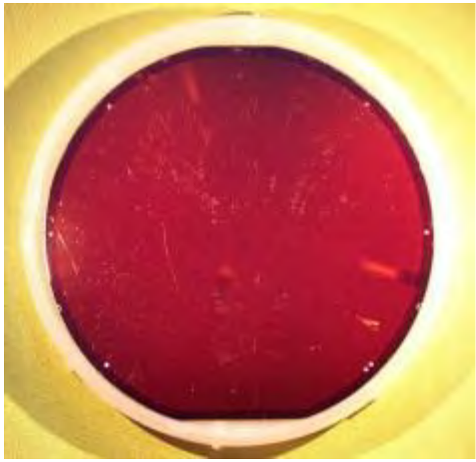
- Clean wafer with solvents (acetone, isopropanol, water)
- Clean wafer with O_2 plasma etch
- Coat/cure Durimide 7510 (photo-definable polyimide) on frontside
- Coat/pattern/cure Durimide on backside
- Etch through backside openings (circles) with KOH etchant
- Remove Durimide from both sides with O_2 and then O_2/CF_4 plasma etches
- Pattern frontside with photoresist using etched through-holes as alignment marks



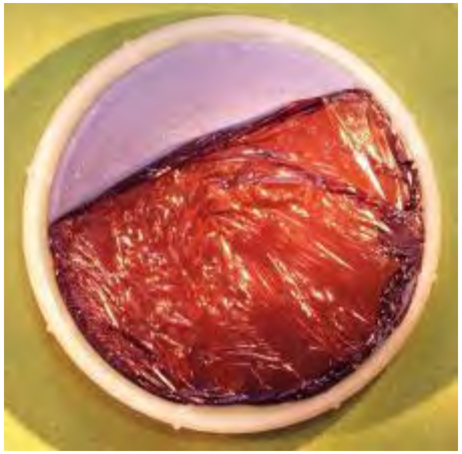
test piece after Durimide development



test piece after Durimide cure



wafer after Durimide cure



shortly after start of KOH etch

Next Steps

- Find different KOH etch mask material (Apiezon W wax, ProTEK, ?)
- Test etch mask viability on small Si piece(s)
- Demonstrate backside alignment methods 1 and 2

Jonathan Oiler:

Enhanced Pathogen Detection with Microfluidics

Presenter:

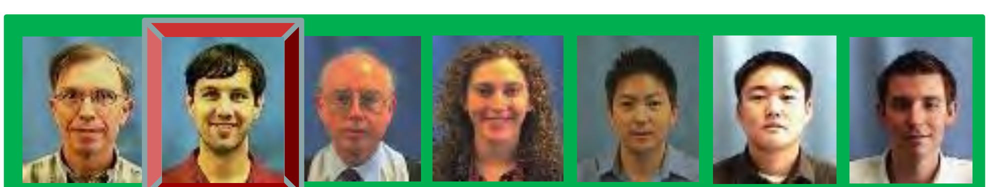
Jonathan Oiler

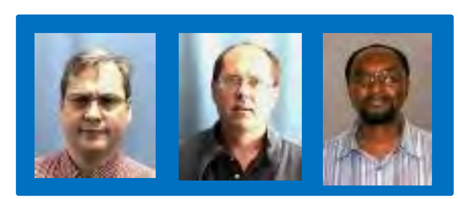
SSC Pacific, Code 71750

Presented to:

SDSU MEMS Course Participants

June 2015



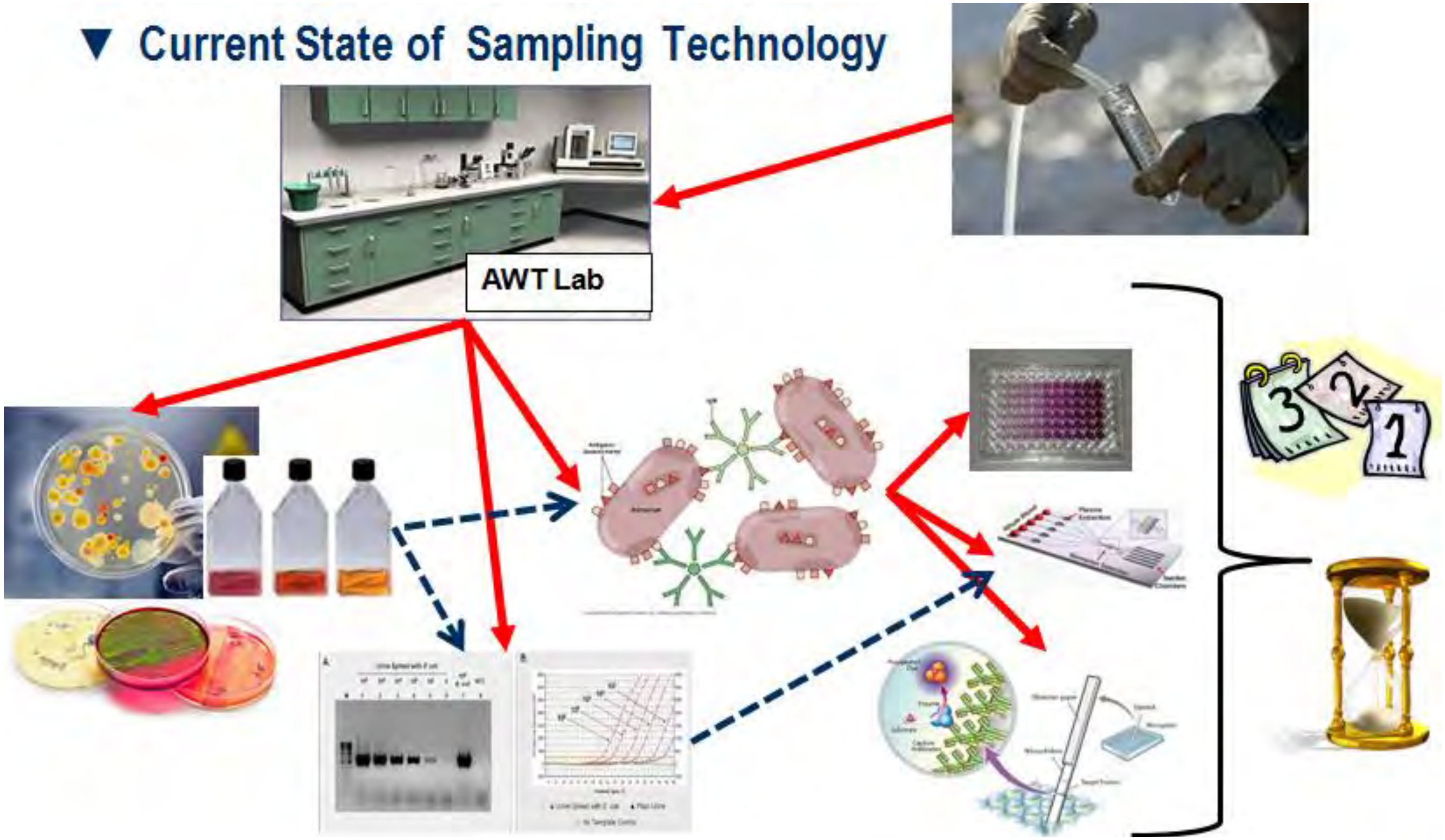


Pathogen Detection

Need: The Navy has a need for a reagent-less, portable, rapid pathogen detection system in order to detect pathogens in aquatic environments for the safety of Navy divers and forward deployed soldiers requiring safe water resources

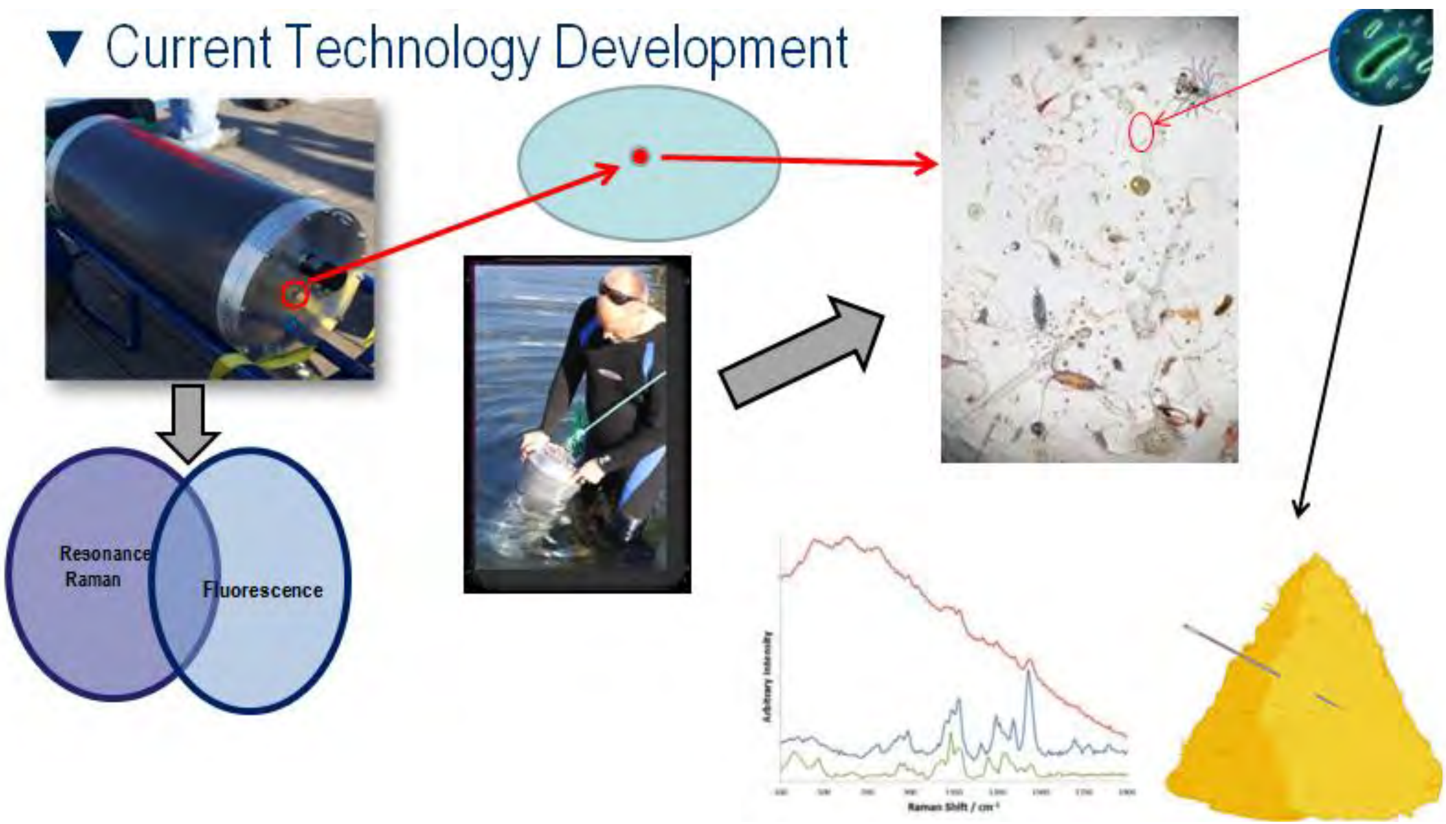
Pathogen Detection – Current

- How are water-based pathogens detected?



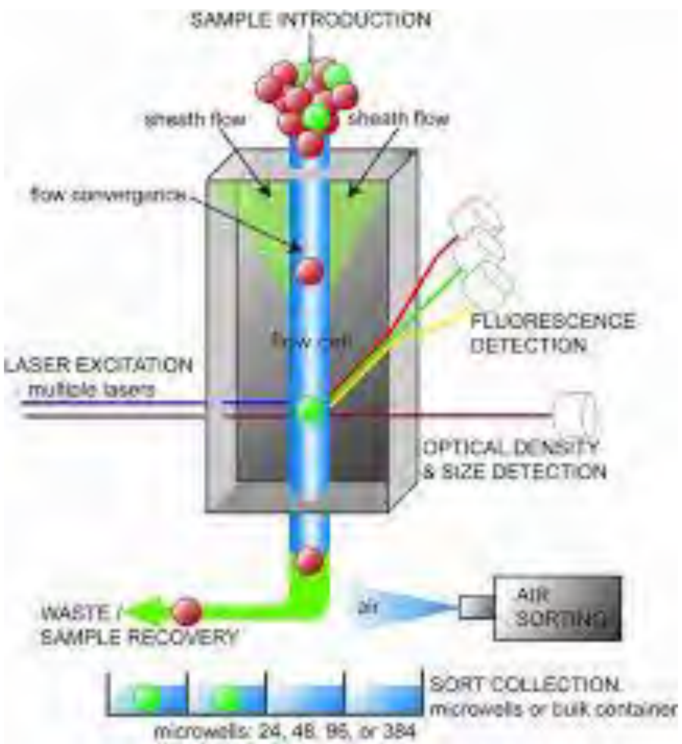
Pathogen Detection – Near Future

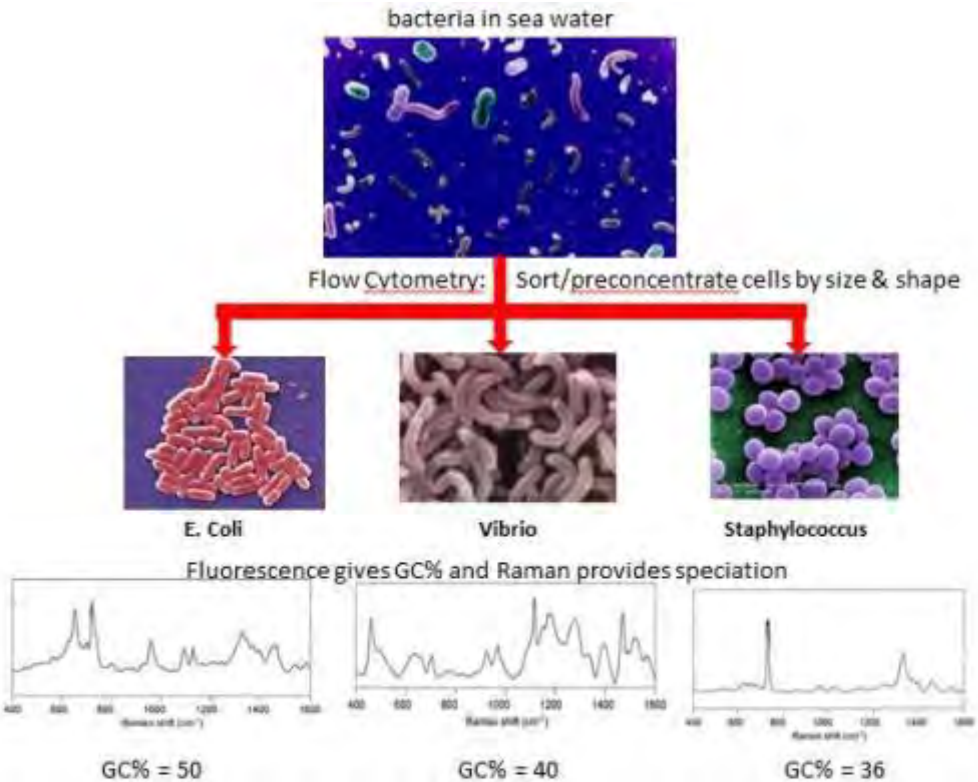
- Portable system developed by commercial company:



Pathogen Detection - Future

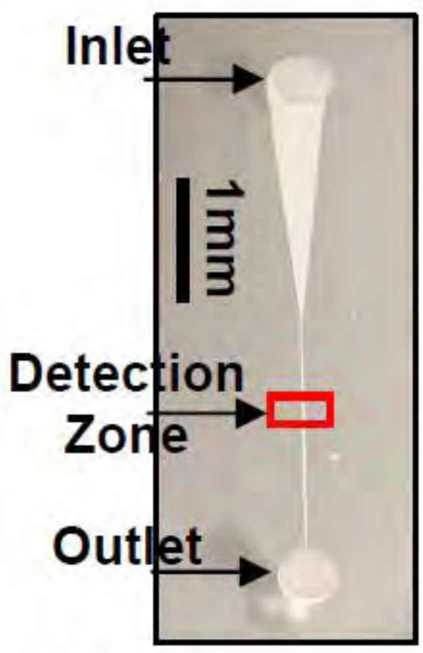
▼ Include flow cytometry and cell sorting/concentrating

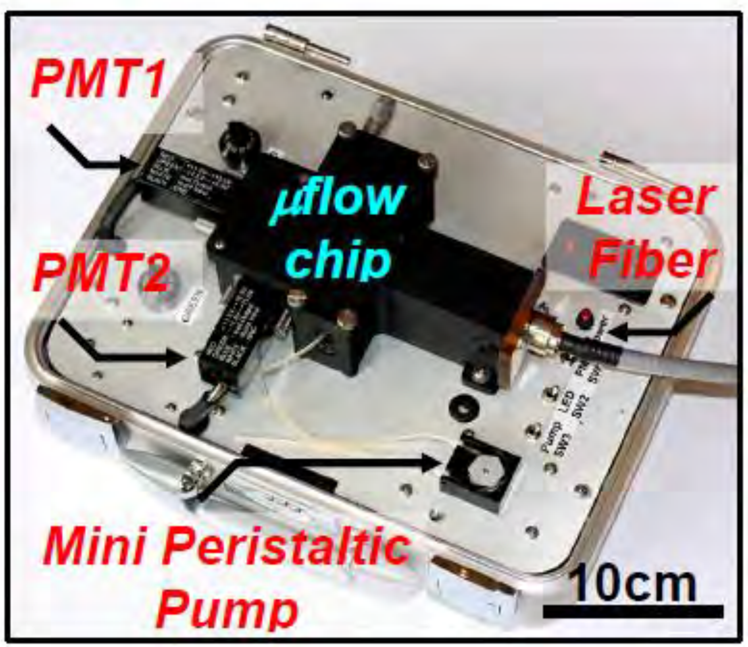




Microfluidic Front End

- Flow Cytometer
  - Companies like CytoChip are developing tiny microfluidic flow cytometry systems



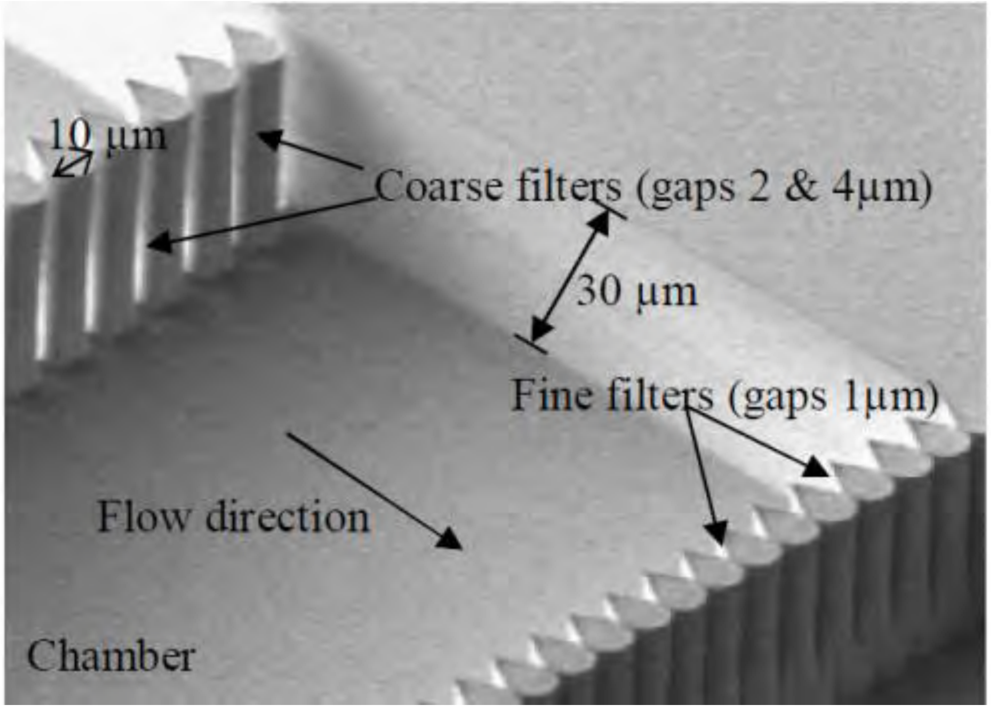


Microfluidic Front End

- Filtering
  - Due to high particle (organic/non-organic) concentration in sea water – pre-filtering is required
  - Secondary micro-fluidic filtering necessary for dealing with small sample size for micro-cytometer systems

Microfluidic Front End

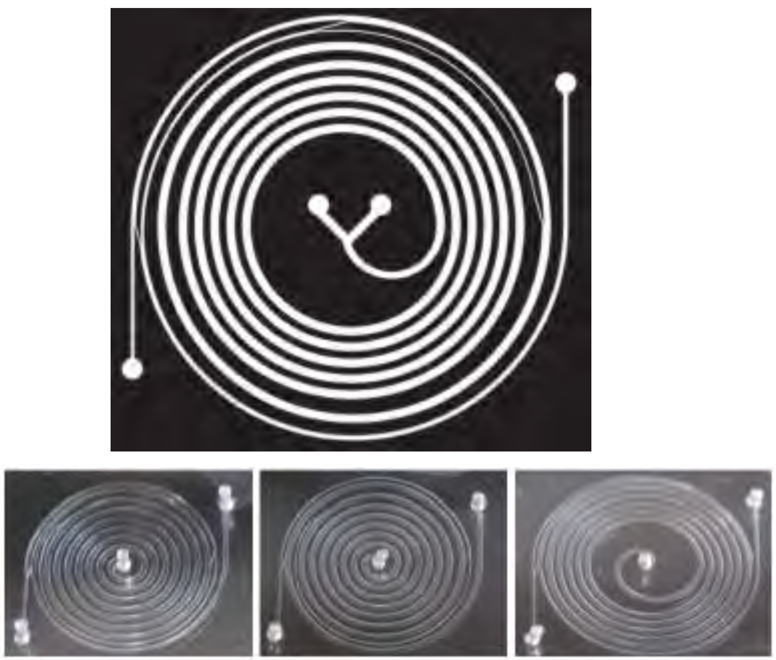
- Microfluidic Filter
  - Eliminate large cells/particles



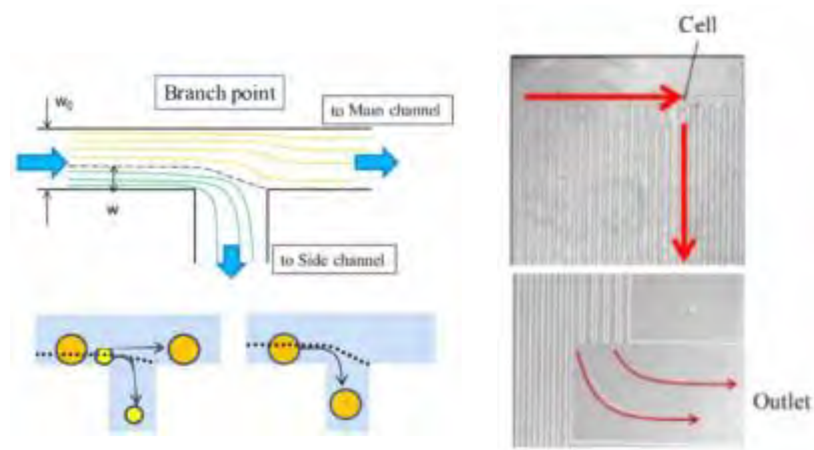
Peh et al., IEEE Transducers, 2007

Microfluidic Front End

- Cell separation/collection/concentration
  - Mechanical means:



Karunanidhi et al., IEEE Nano/Mol. Med and Eng., 2013



Hasegawa et al., Micro/Nano Mechatronics Hum Sci.., 2013

Howard Dyckman:

Suspended Infrared Waveguides

Presenter:

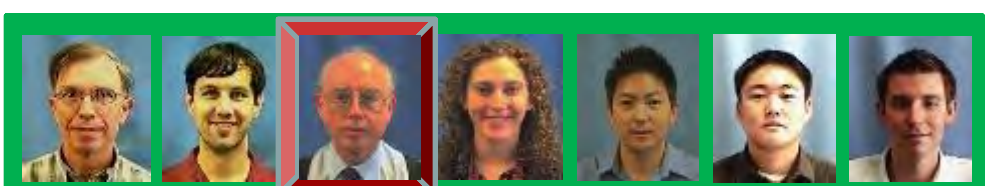
Howard Dyckman

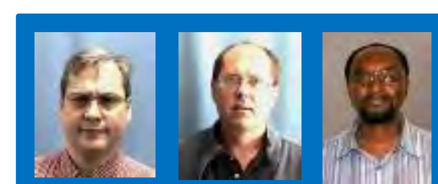
SSC Pacific, Code 71730

Presented to:

SDSU MEMS Course Participants

June 2015





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Objective & References

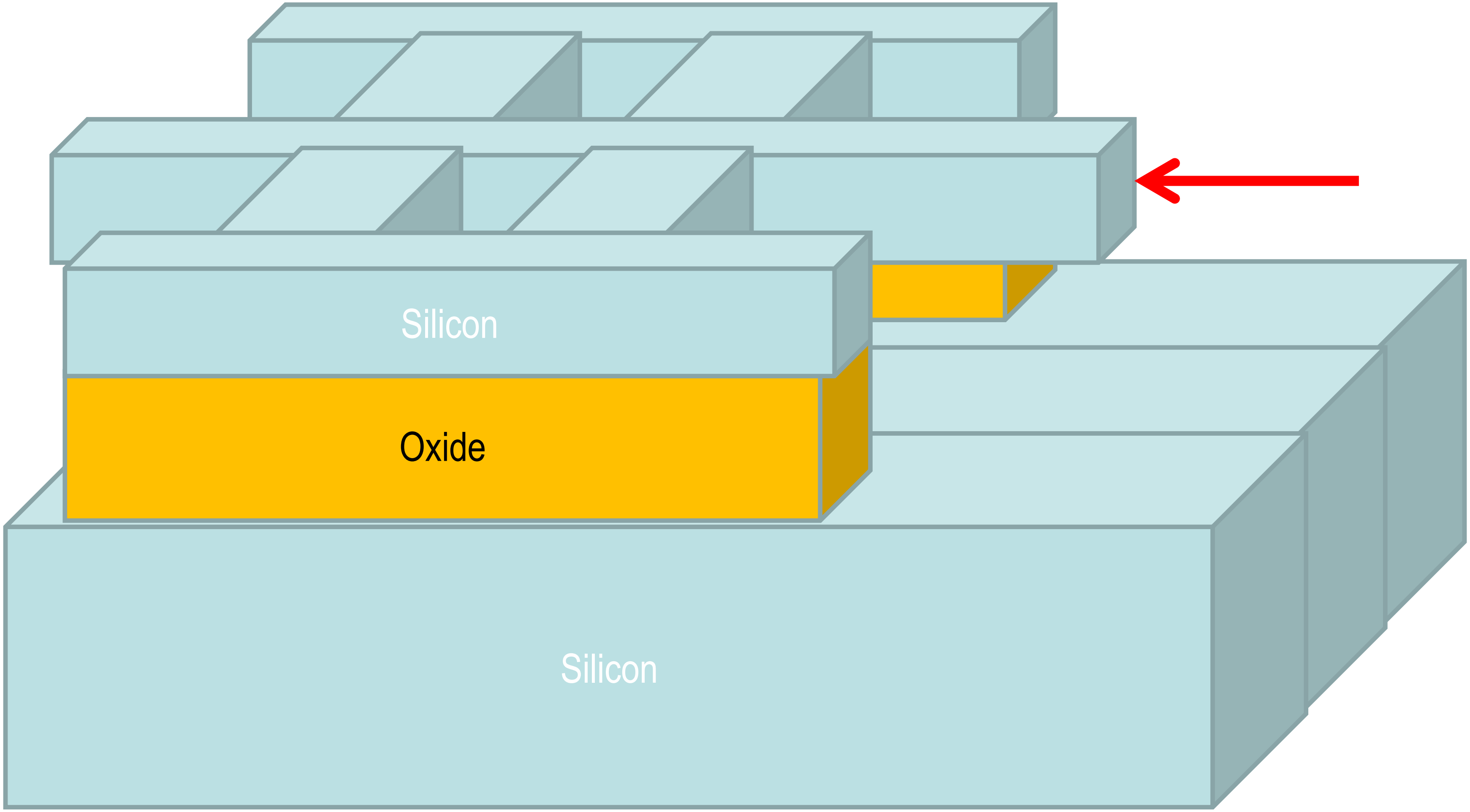
- Objective: Develop fabrication procedures to make suspended waveguides for infrared in wavelength range 1-5 um.

▼ J. Soler-Penades et al. (2014). Suspended SOI waveguide with sub-wavelength grating cladding for mid-infrared, *Optics Letters* 39:19

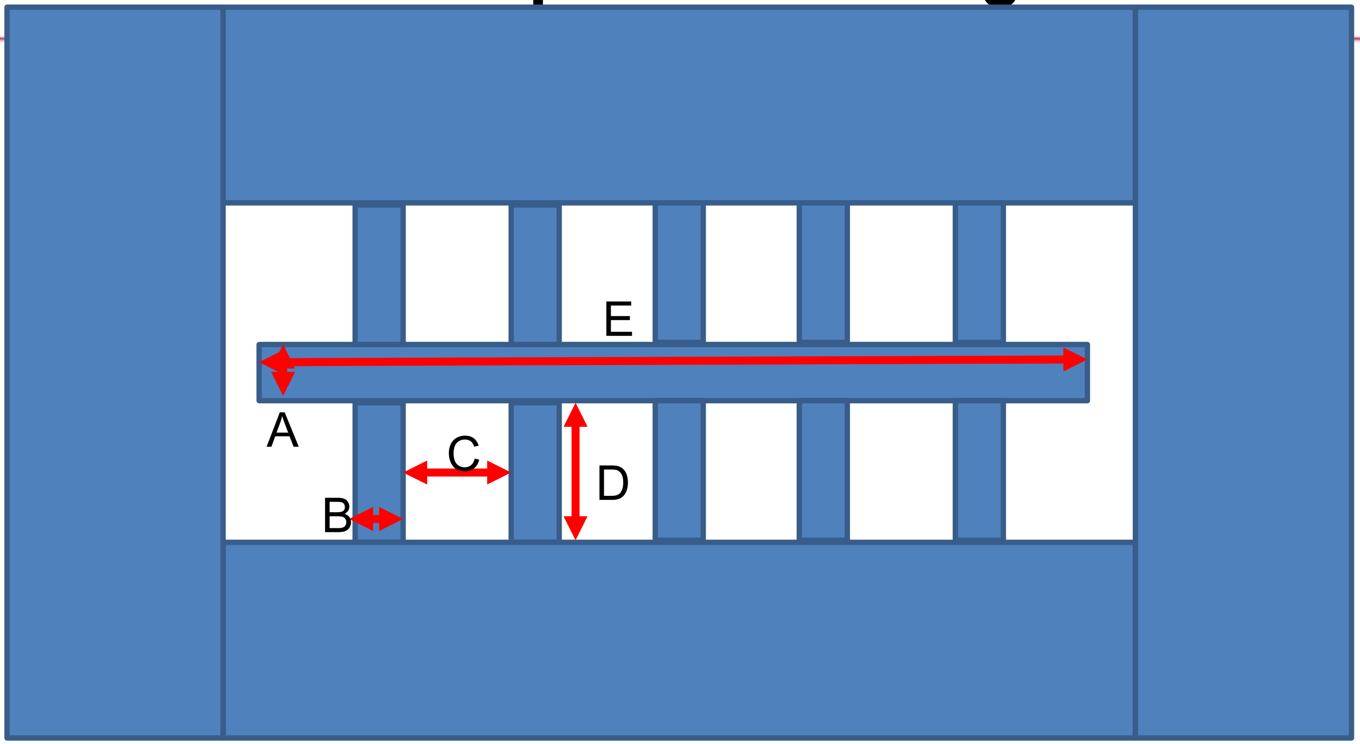
▼ S. Zlatanovic et al. (2013). Silicon-on-Sapphire Waveguides for Widely Tunable Coherent Mid-IR Sources, SSC Pacific TD 3275

▼ S. Zlatanovic et al. (2014). Silicon-on-Sapphire Waveguides: Mode-converting Couplers and Four-Wave Mixing, SSC Pacific TD 3283

Suspended Waveguide for Infrared



Pattern for Suspended Waveguides

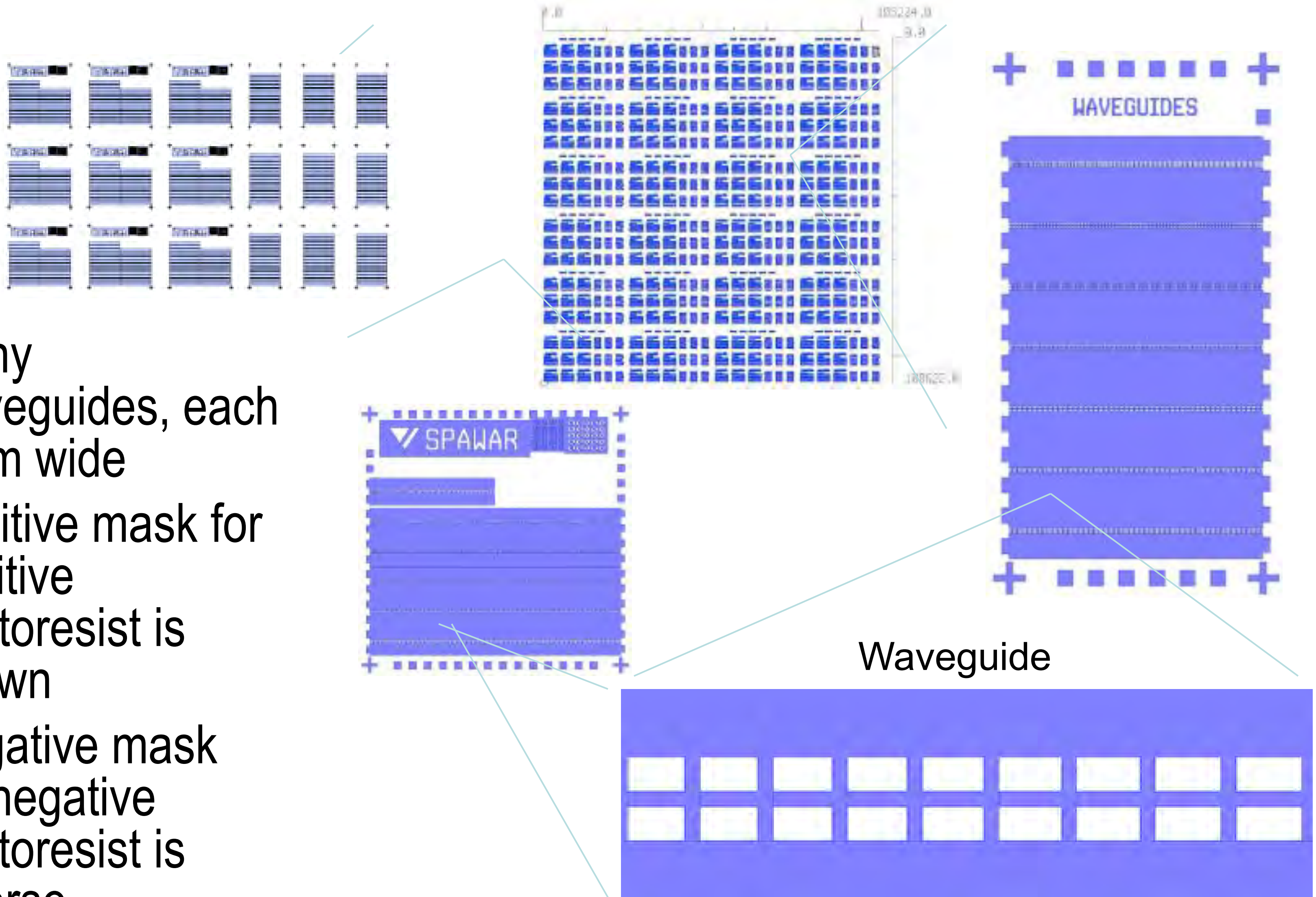


Suspended waveguide with horizontal supports

A: 5 um; B: 5–10 um; C: 10–50 um; D: 15–20 um; E: 2–4 mm

Goal: develop fabrication methods; 5-um lithography limit prevents making single-mode waveguides for 1- to 5-um IR

Mask for 4" Wafer



- Many waveguides, each 5 um wide
- Positive mask for positive photoresist is shown
- Negative mask for negative photoresist is inverse

Wafers

- Silicon wafers
  - SiO_2 layer 3659 Angstrom
  - Si top layer 2165 Angstrom
- Photolithography done on four wafers
  - 1. Shipley S1813 (positive photoresist)
  - 2. Shipley S1813 (positive photoresist)
  - 3. SU-8-10 (negative photoresist)
  - 4. PMGI + Shipley S1813 (positive photoresist with PMGI underlayer)

Overall Procedure

- Protect waveguides and supports
  - Positive mask for positive photoresist (Shipley S1813; Shipley S1813 with PMGI underlayer)
  - Negative mask for negative photoresist (SU-8-10)
- Etch around waveguide and supports, through top Silicon layer, using CF_4 plasma; may etch partway through lower SiO_2 layer
- Etch SiO_2 around and under waveguides and supports
- Examine in Scanning Electron Microscope (SEM) for degree of etch

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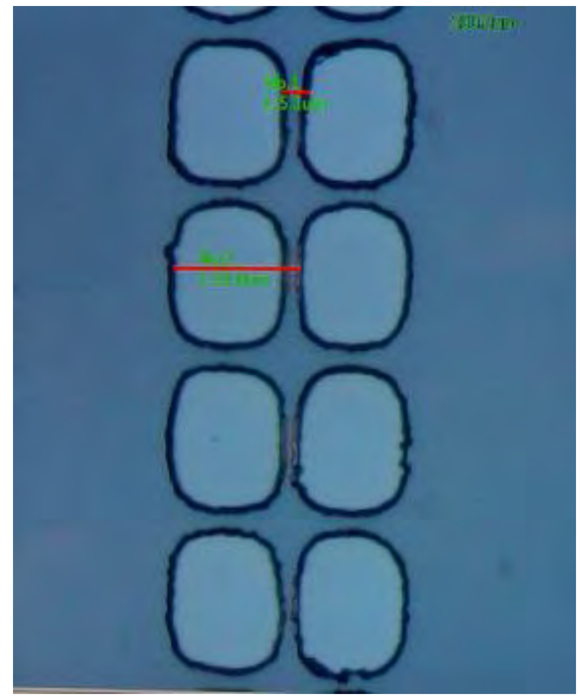
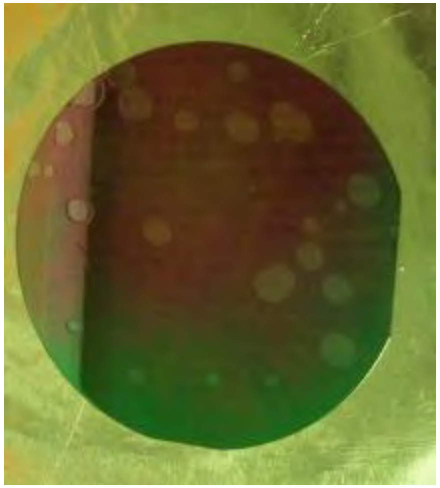
Waveguide After Exposing Shipley S-1813 Photoresist

- Spin 2000 rpm Shipley S-1813 for 45 sec to produce 2-um coating
- Prebake 115 °C for 60 sec
- Shipley MF-319 Developer
- Shown is one of the cleaner looking photoresists before etching
- Limited optical resolution of lithography (approx. 5 um) causes rounded corners
- Horizontal center-to-center of ovals measures 24 mm; Waveguide width measures 5.1 mm (viewed in optical microscope)

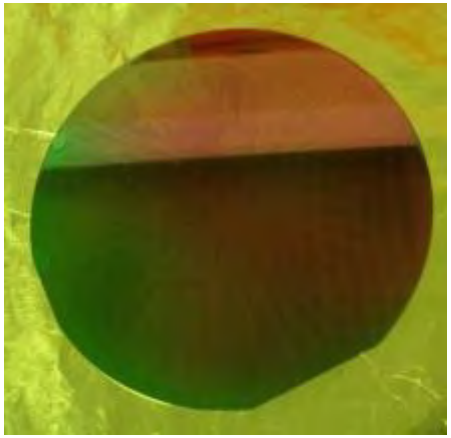


Pre-Baking SU-8: Slow Is Better

- SU-8 shrunk (many holes) due to fast pre-baking, approximately as follows:
  - 65 °C for 2 to 3 min
  - 95 °C for 5 to 6 min

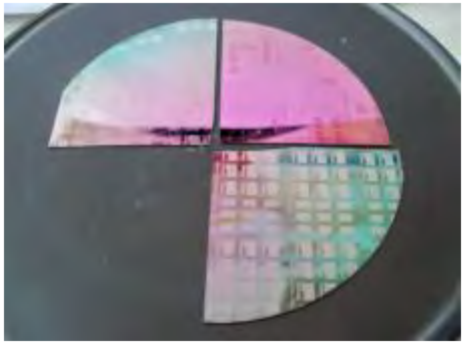


- SU-8 shrunk very little (few holes) due to slower pre-baking
  - 45 °C for 8 min
  - 65 °C for 2 min
  - 95 °C for 3.5 min
  - 105 °C for 8 min



CF4 Etch of Top Silicon Layer

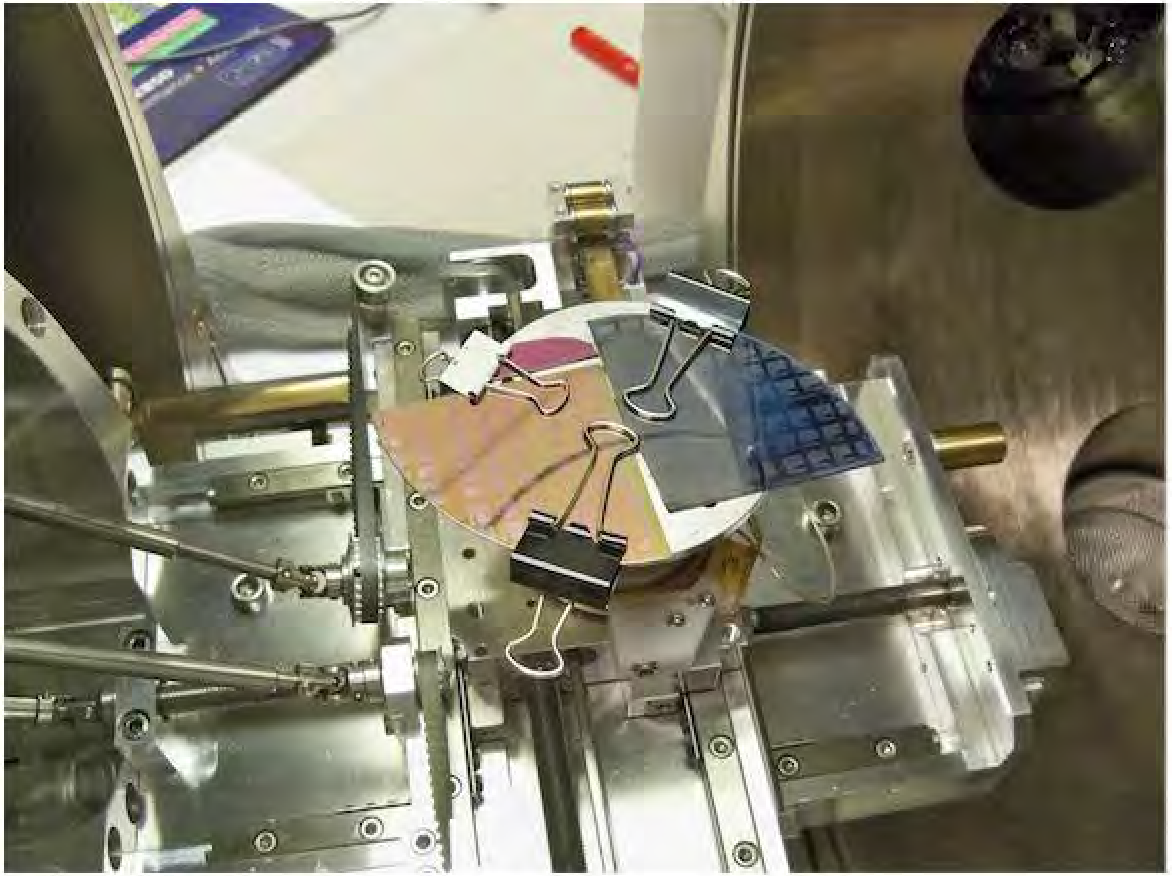
- Technics Series 85-RIE plasma etcher
- CF_4 plasma etch: about 470-490 mTorr, 50 W, 16 minutes
- CF_4 etch "burnt" some wafers
- Proposed Solution: Etch for less time, add O_2 to plasma



Before

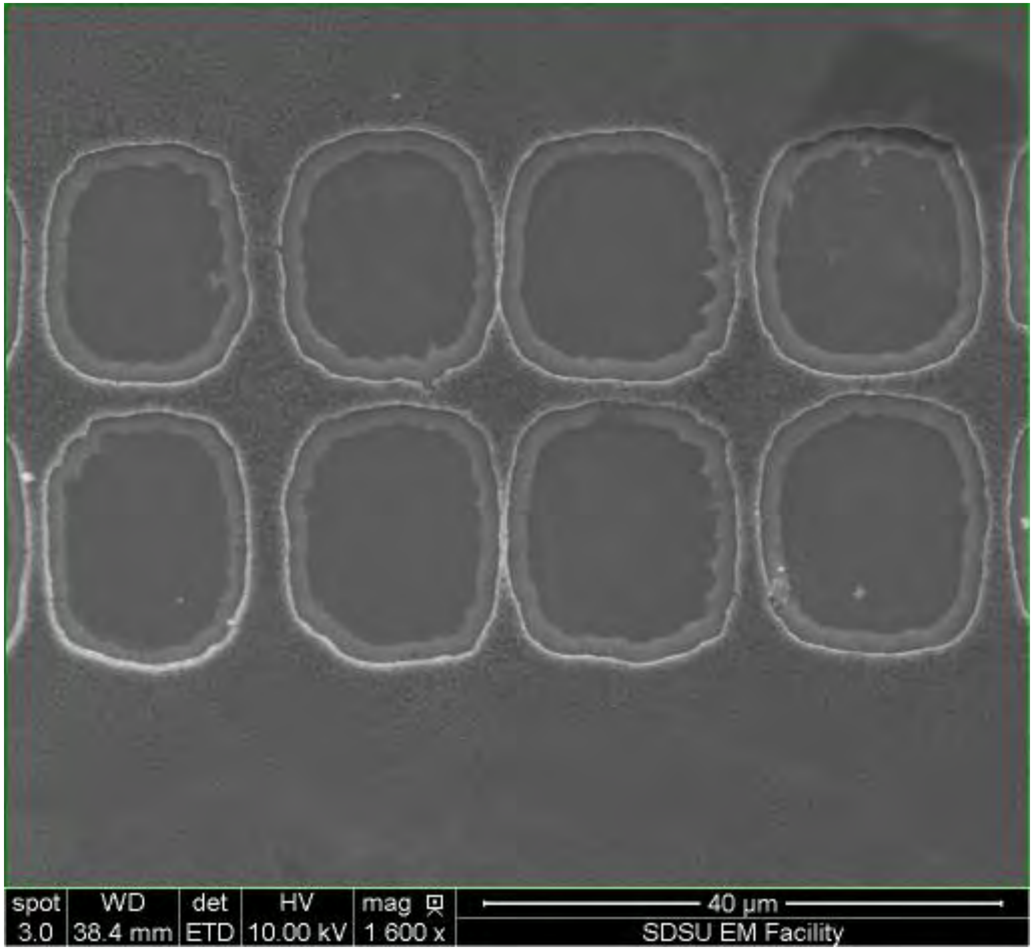
After

Mounting Wafers in SEM



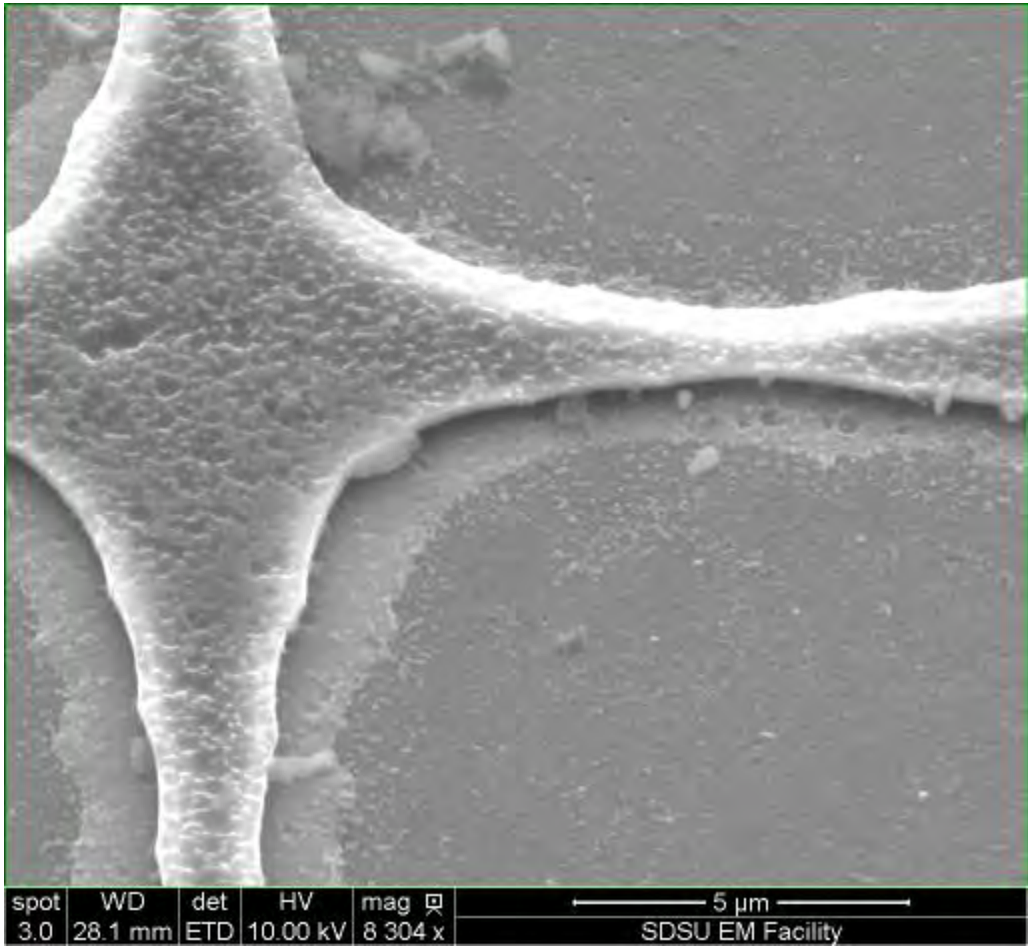
SEM Photo: Shipley

- Shipley S-1813 positive photoresist with CF_4 etch and HF vapor etch, not tilted in SEM
- Most likely shows top Si layer, ring from SiO_2 layer, and Si wafer exposed inside ring



SEM Photo: Shipley

- Shipley S-1813 positive photoresist with CF_4 etch and HF vapor etch, tilted 45 deg in SEM
- May be showing slight undercut

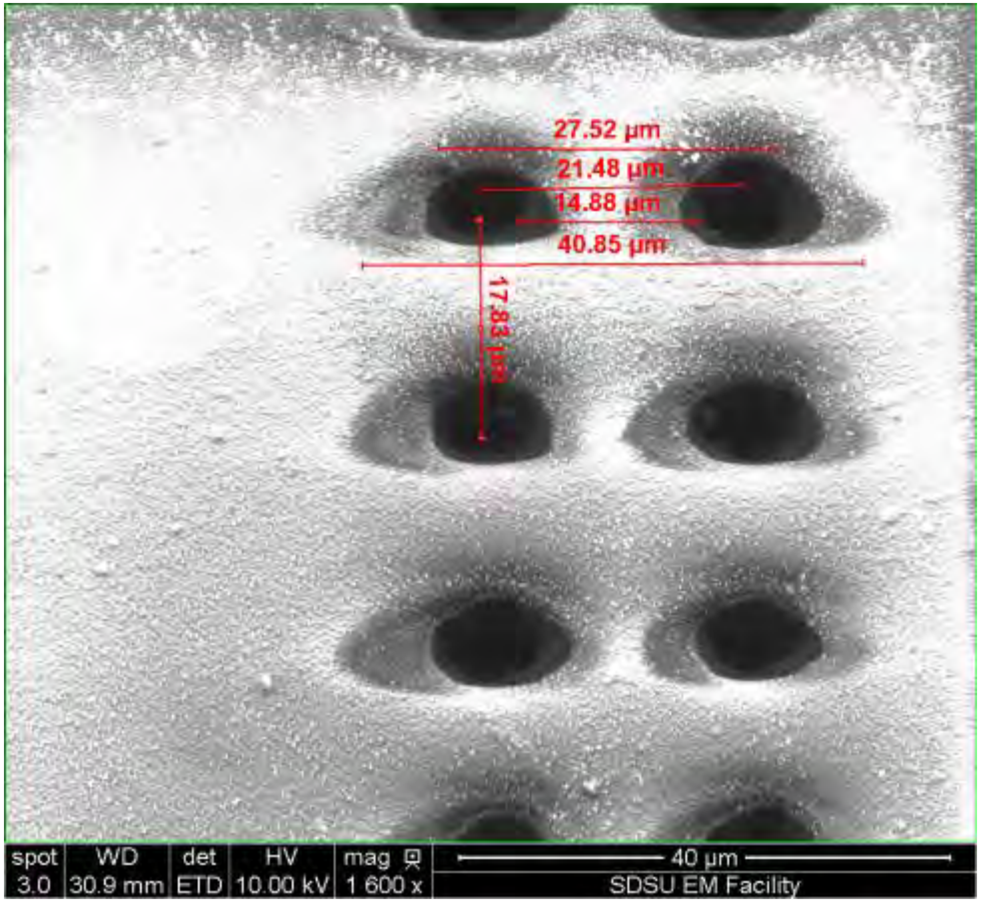


SEM Photo: PMGI+Shipley

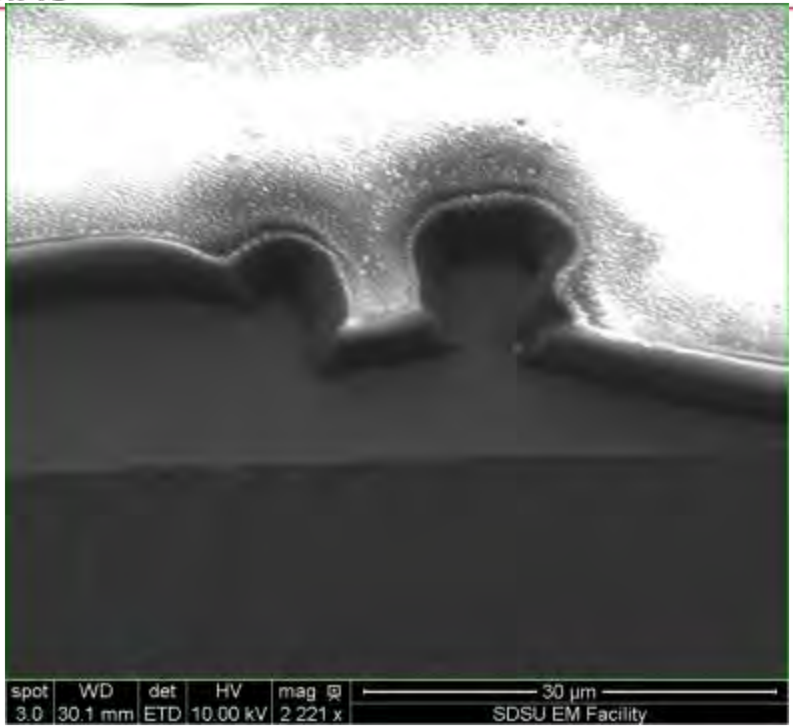
- PMGI + Shipley S1813 positive photoresist with CF_4 etch and HF vapor etch, not tilted in SEM
- Perhaps has etched Si and SiO_2 layers

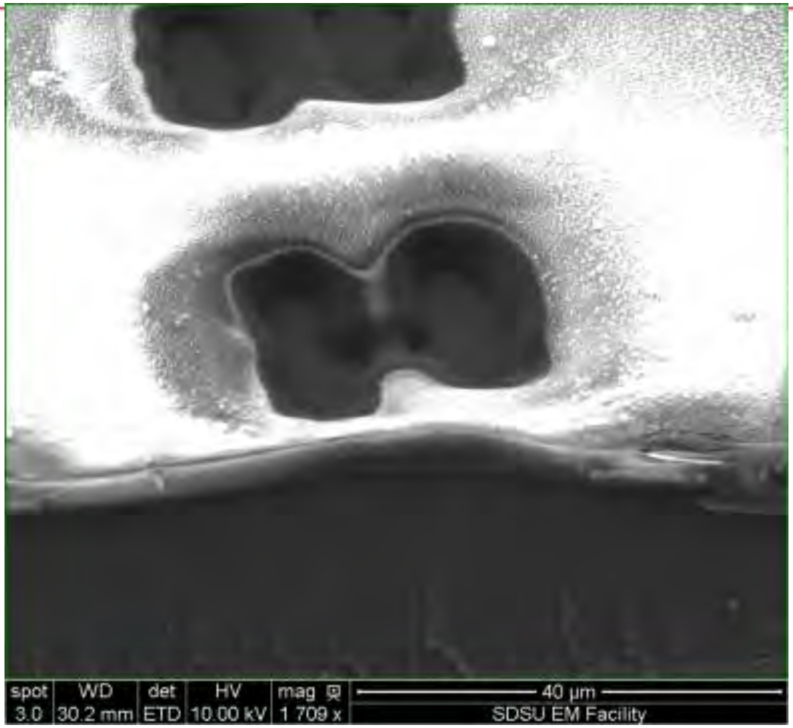
SEM Photo: SU-8-10

- SU-8-10 negative photoresist with CF_4 etch and HF vapor etch, tilted 45 deg, with measurements



SEM Photo: SU-8-10





- SU-8-10 negative photoresist with CF_4 etch and HF vapor etch, tilted 45 deg
- Shows 3-D structure of SU-8 layer but unclear what was etched and probably no undercut

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Lessons Learned

- Add O_2 to CF_4 plasma etch of Si to moderate it – avoid burnt effect.
- HF vapor etch for SiO_2 can roughen silicon surface; find a liquid etch for SiO_2 that does not attack silicon. (Or, can leave photoresist on during HF vapor etch to prevent roughened waveguide surfaces, but hard to remove it from suspended structures afterwards.)
- Etch SiO_2 for longer time to get good undercut.
- SU-8 negative photoresist needs slow pre-bake with gradual raising of temperature to prevent shrinking. Bake "well done" to prevent sticking to mask. But exposed SU-8 is difficult or impossible to remove and would alter waveguide properties; use a different photoresist.

QUESTIONS

- Why wasn't there more undercut?

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Lessons Learned, cont'd

- Higher resolution photolithography needed to make good IR waveguides - avoid rounded corners, make narrow waveguides for single-mode.
- Make waveguides longer to enable dicing and testing with infrared.
- Cut across waveguides and mount samples at 90 deg in SEM to see cross section better.
- Consider cleaning blank wafers with O_2 etch after Acetone/Isopropyl/DI H_2O.

Possible Follow-On Work

- Procure wafers with SiO_2 and Si layers with thicknesses more appropriate for IR waveguides (1 to 2 um).
- Use glass or quartz mask for 1 um lithography.
- Find better etch for SiO_2 and proper duration.

Acknowledgments

- Professor Sam Kassegne of SDSU and students
- Paul Swanson, Bruce Offord, and colleagues
- SSC Pacific Workforce Development program

Teresa Emery:

Safe Cantilever Release Using KOH

Presenter:

Teresa Emery

SSC Pacific, Code 71730

Presented to:

SDSU MEMS Course Participants

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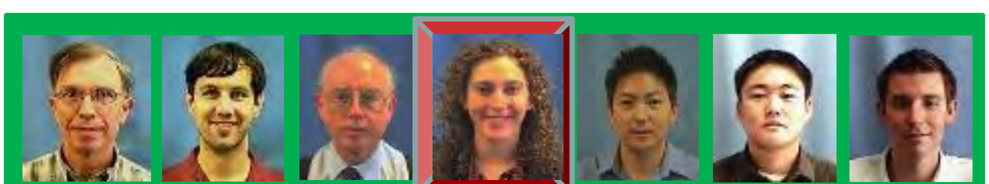
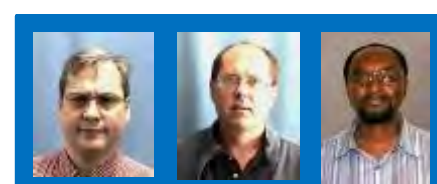
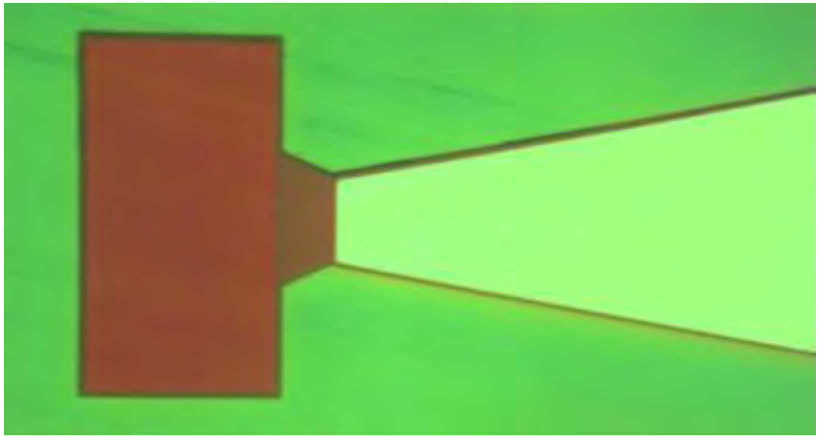




Bistable MEMS systems for Energy Harvesting

Non-linear devices are showing promise for responding to low frequency vibrations for energy harvesting applications. Most MEMS scale energy harvesters take the form of cantilevers operating in their resonant frequency, but such operation is usually confined to the higher frequencies due to their small size. Non-linear energy harvesters do not operate at their resonant frequency and can harvest lower frequency vibration while still being MEMS scale. One way to introduce non-linearity into a MEMS scale device is to make it bistable. This bi-stability can be created in several ways including shape, magnet repulsion and attraction, and material stress. Each methods benefits and drawbacks will be discussed as it applies to energy harvesting and ease of fabrication.

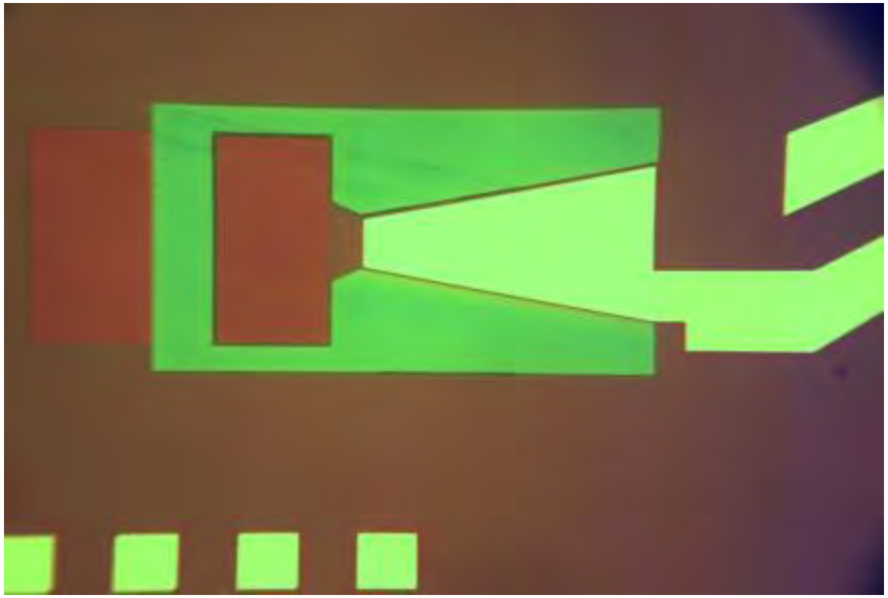


Why use KOH Release the Cantilever?

- KOH creates a very selective etch between silicon and silicon nitride.
- Low stress nitride is good insulating material used as a structural component of MEMS devices
- KOH bath can release several wafers at a time with very repeatable results
- The last step in all MEMS fabrication procedures is the release. Devices are too fragile to process after release.

Protecting Devices from KOH

- KOH is a common wet silicon etch, very corrosive. Top side electronic must be covered to prevent damage
- Two different spinable polymers are possible solutions: Durimide and ProTEK
- Sample piece will be covered and put in the KOH bath to test durability of the polymer
- The sample must also survive the removal of the polymer by solvent bath or oxygen plasma.



Technical Execution

Sam Chieh:

mm-Wave Antennas on Quartz Substrate

Presenter:

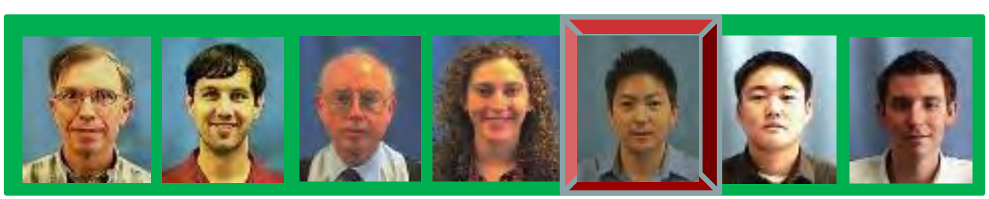
Sam Chieh

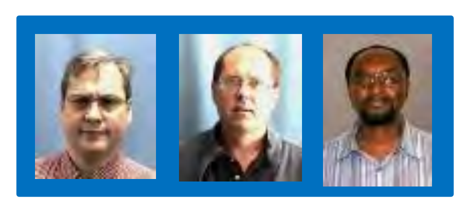
SSC Pacific, Code 55250

Presented to:

SDSU MEMS Course Participants

June 2015

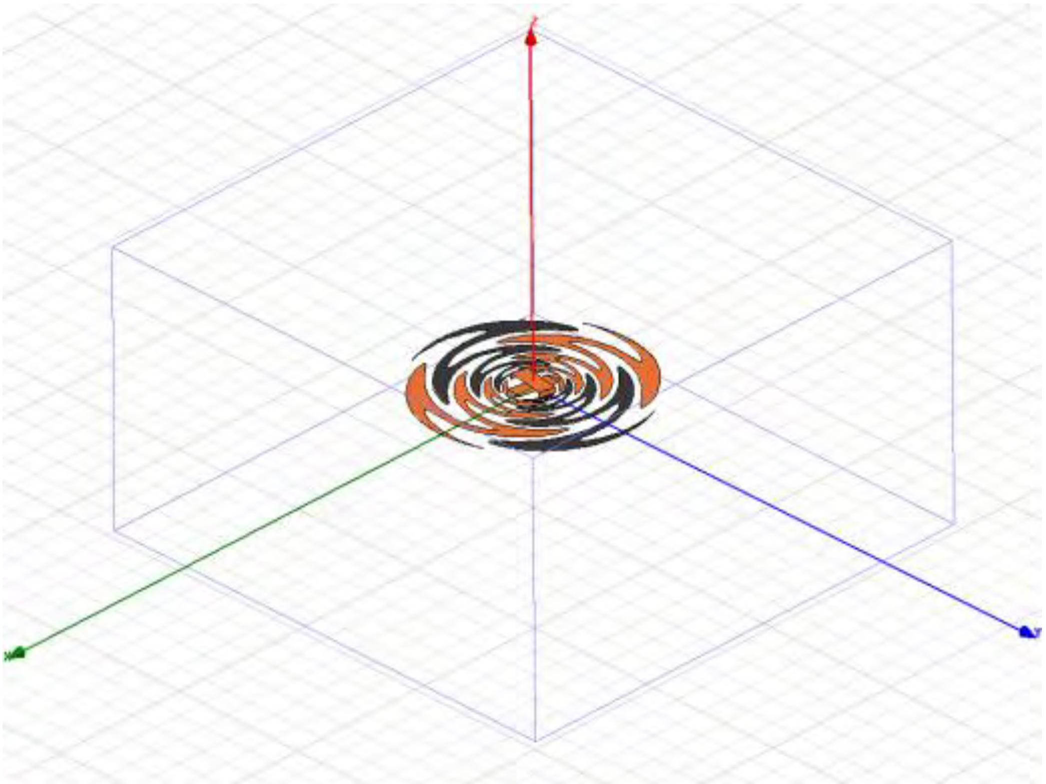




mm-Wave Antennas on Quartz Substrate

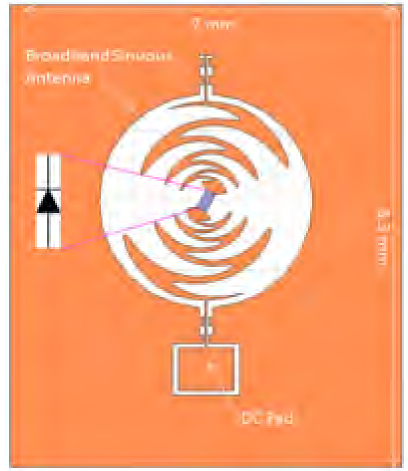
Future innovative Navy systems will need to operate at high millimeter wave frequencies due to recent advancement and adoption of millimeter-wave and sub-millimeter wave communication systems, radars, and imaging systems

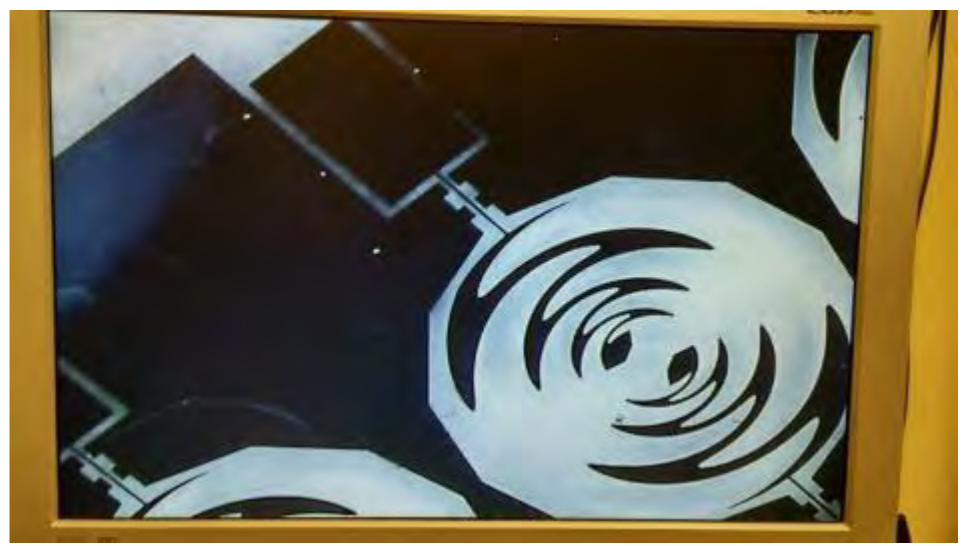
We propose the design and development of monolithic wideband antennas for mm-Wave operation, and more specifically in the W-band (75–110 GHz). Shown is a conceptual diagram of how the sinuous antenna may look.



MEMS Fabrication – Sinuous Antenna

- **Lift-Off process**
  - Plasma Etch Wafer
  - PMGI Photoresist (150 ˚C for 5 min)
  - Shipley 1813 Photoresist (115 ˚C for 90s)
  - Expose and develop
  - Chromium Sputtering (10 u, 20 u)
  - Aluminum Evaporation
  - Acetone Wash
- **Observations**
  - Plasma etching critical for clean wafer
  - Sensitive photoresist baking times
  - Chromium sputtering necessary for aluminum to adhere
  - Chromium sputtering 30 u caused burning. Needed 2 instances (10 u and 20 u)





SPAWAR
Systems Center
PACIFIC

Everly Yeo:

mm-Wave Antenna Arrays for Millimeter Wave Camera

Presenter:

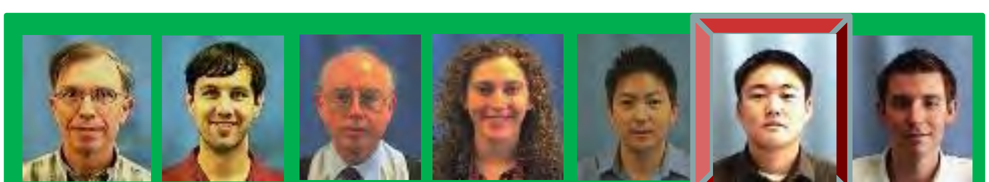
Everly Yeo

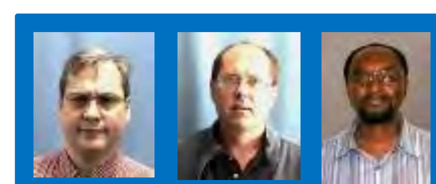
SSC Pacific, Code 55250

Presented to:

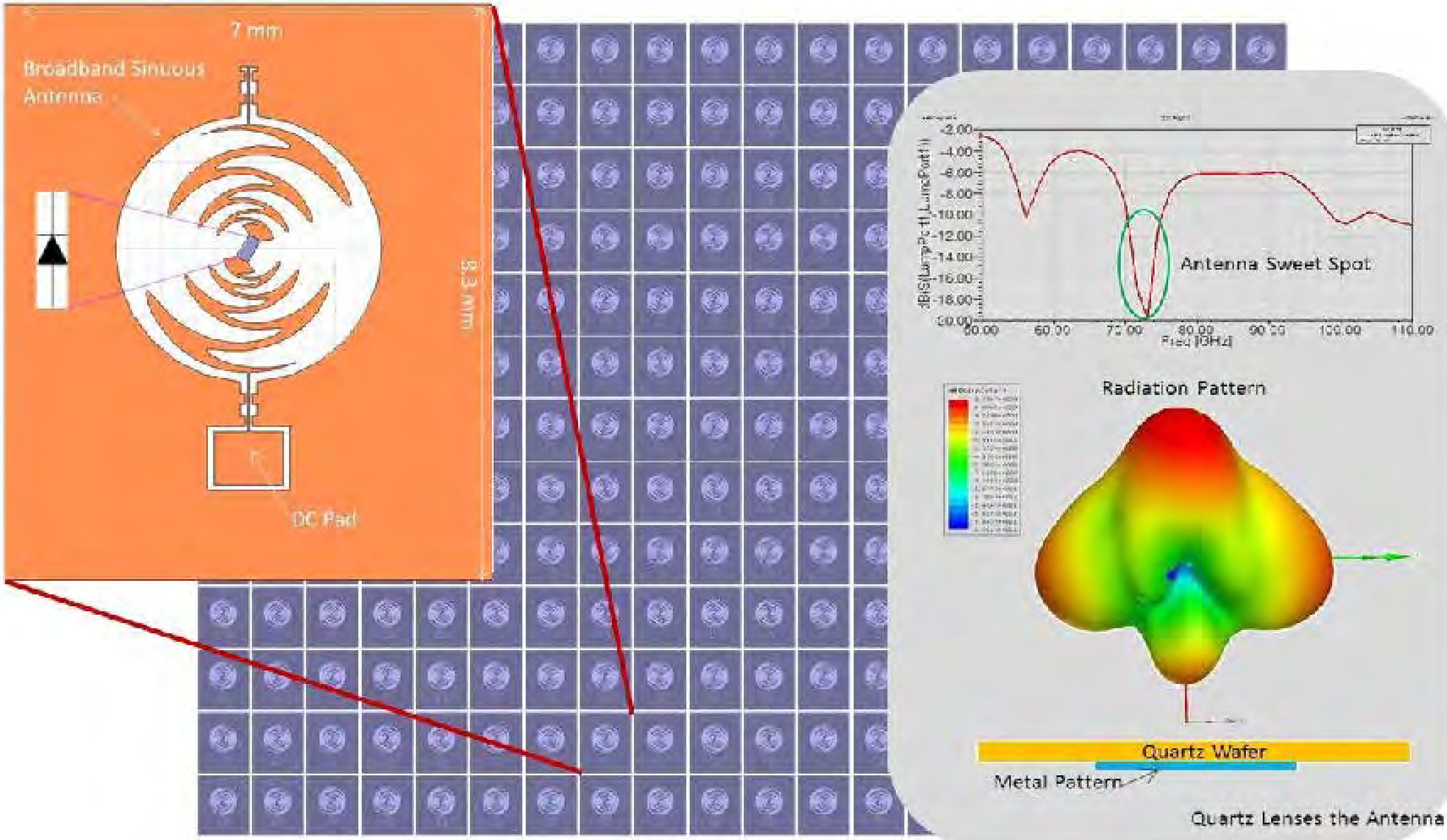
SDSU MEMS Course Participants

June 2015



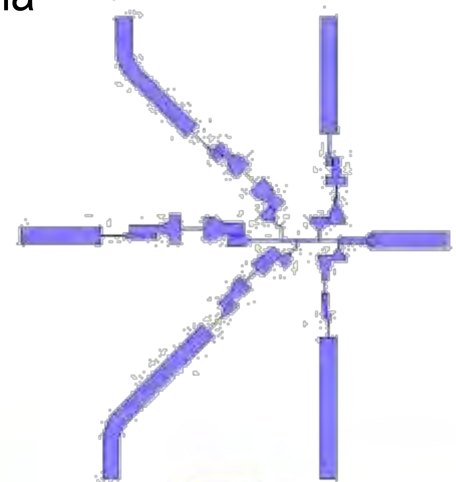


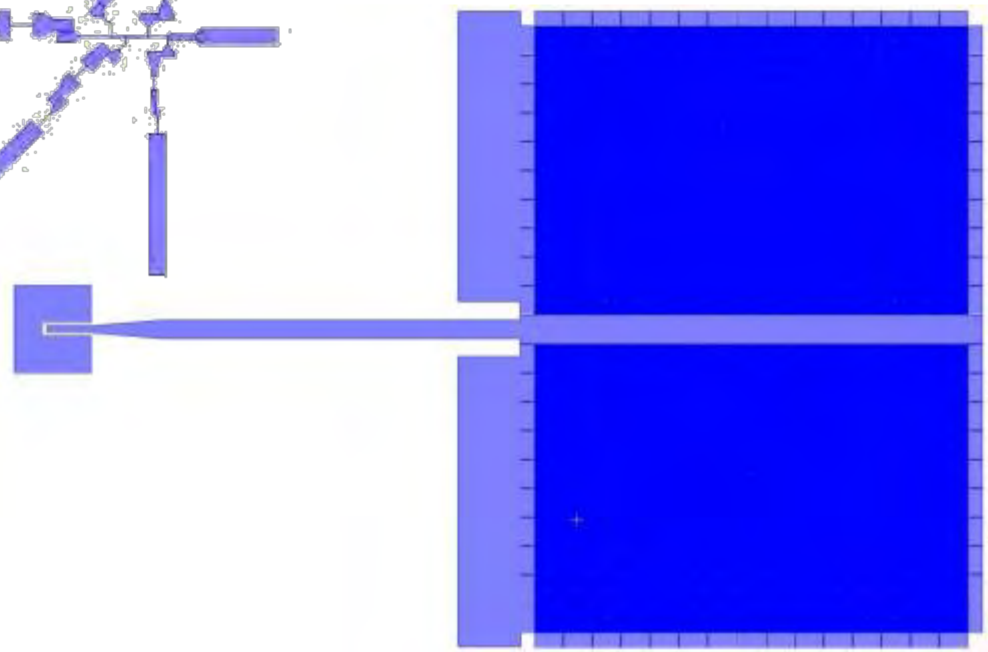
Antenna Array for Use with Pin-Hole Camera

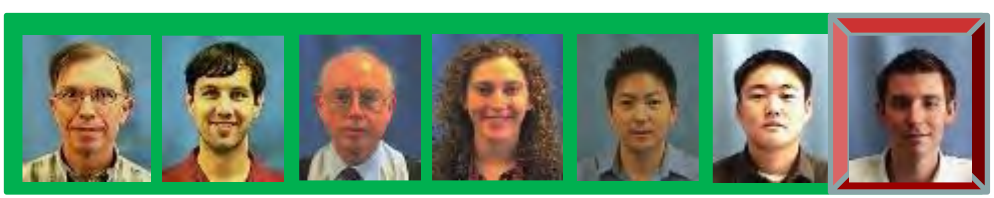


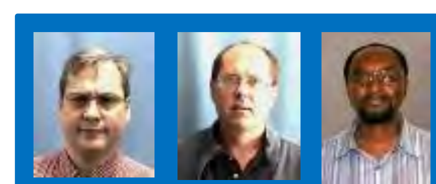
SPAWAR Systems Center PACIFIC

Ben McCoy: MEMS for Antenna









Summary

The objective of this work force development project was to further develop and offer a course for SSC Pacific S&T professionals to broaden their skills, experience, and understanding of Micro-Electro-Mechanical Systems (MEMS) through instruction and hands on experience in MEMS and semiconductor fabrication. It also had the objective of providing a means to access local university fabrication capabilities that will continue after this workforce development project is completed. By making the students familiar with the capabilities of accessible semiconductor fabrication labs, less money in the future will be needed to outsource MEMS fabrication, and more creative solutions and technology will be developed by SSC Pacific S&T scientists and engineers.

REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2015

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Micro-Electro-Mechanical Systems (MEMS) Fabrication
Course Projects Review FY15

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

TD 3298

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Innovative Science and Engineering (NISE) Program
Space and Naval Warfare Systems Center Pacific (SSC Pacific)
53560 Hull Street
San Diego, CA 92153-5001

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In Fiscal Year (FY) 2015, the third year of a three-year Naval Innovative Science and Engineering (NISE) Program Workforce Development project, Space and Naval Warfare Systems Center (SSC Pacific) held a course on micro-electro-mechanical (MEMS) and semiconductor device and fabrication techniques to assist its Science and Techno (S&T) scientists and engineers to technologies that increase the capabilities of the U.S. Navy warfighters. The objective of this workforce development project is to further develop and offer a course for SSC Pacific S&T professionals to broaden their skills, experience, and understanding of MEMS and lithography-based device fabrication through instruction and hands-on experience. The course was 14 weeks, consisted of 16 hours of lectures at SSC Pacific, and 32 hours at a local semiconductor fabrication facility with an external user program (in this case, at the San Diego State University [SDSU] MEMS lab). The SSC Pacific and SDSU instructors were experienced in semiconductor processing and MEMS design. The students became familiar with the capabilities of semiconductor fabrication, allowing device development using less money (compared to outsourcing) and more hands-on interaction and process ownership. The course was not for the students to complete their projects in the initial 14 weeks, but to act as a launching pad for new innovations that will assist funded projects and stimulate the creation of new funded projects.

15. SUBJECT TERMS
Mission area: Micro-electronics
wafer etching
Infrared waveguides
micro-fluidic flow channel source tracking
miniaturized flow cytometer
mm-wave antenna arrays
bistable MEMS systems
energy harvesting
MEMS for antennas
mm-wave antennas
quartz substrate

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Paul D. Swanson
					19B. TELEPHONE NUMBER *(Include area code)*
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